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CRITERIA FOR THE DESIGN OF A STRAIN ATTENUATING OBTURATOR

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13. ABSTRACT *(Maximum 200 words)*

Dramatic reductions in dynamic strains in gun tubes are shown to be possible when the ballistic pressure rise in the vicinity of the projectile is made less abrupt. Numerical examples are given for the case of a ramp-step ballistic pressure loading in a 60-mm gun tube as the projectile velocity nears critical.

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INTRODUCTION AND BACKGROUND

Previous publications by Simkins [1-3] have shown good agreement between measured dynamic strains in gun tubes and those predicted by critical velocity theory when the projectile velocity is subcritical. Moreover, even thin-wall theory predicts these dynamic strains with surprising accuracy. However, because critical velocity theory ignores end effects (an infinitely long tube is assumed), differences do occur between the measured and predicted strains. These are most easily explored via finite element simulations, which are assumed to more closely mimic physical reality. Fcr the purpose of exposing the basic idea behind such an obturator, however, the infinitely long and uniformly thin-walled tube traversed by a moving pressure at constant velocity is most convenient.

SECTION I - WALL DEFORMATION IN A GUN TUBE OF INFINITE LENGTH (CRITICAL VELOCITY THEORY)

Figure 1 shows the theoretically predicted radial displacement along the length of an infinitely long and uniformly thin-walled gun tube caused by a unit pressure step moving at a velocity which is 99% of the critical value, i.e., $V = 0.99V_{cr}$. The displacement values have been normalized with respect to the displacement as calculated from the Lamé formula [4] so that the ordinate can be labeled the *dynamic amplification*. The abscissa ξ measures the distance from the leading edge of the step so that the deformation appears constant to an observer moving along with the step. To such an observer, the deformation is reminiscent of a static load-deformation scenario. This equivalence to a static problem (really an application of D'Alembert's Principle) can also be stated mathematically. Starting with the differential equation of motion for a thin-walled tube:

$$D\frac{\partial^4 w}{\partial x^4} + \frac{Eh}{R^2}w + m\frac{\partial^2 w}{\partial t^2} = (1 - H(x - Vt)) \tag{1}$$

where H is the Heaviside step function:

$$H(x - Vt) = 0 \quad x < Vt$$

$$= 1 \quad x > Vt$$

In this equation, w is the radial displacement of the median surface of the cylinder located at a distance R from the central axis; h is the wall thickness and is assumed small compared to R; $m = \rho h$ where ρ is the mass density of the tube material; $D = Eh^3/12(1 - \nu^2)$; E is Young's modulus of elasticity; ν is Poisson's ratio; and V is the velocity of the moving pressure, assumed to be finite and constant.

The critical velocity derived from this thin-wall theory is given by the expression:

$$V_{cr}^2 = \frac{2}{\rho h}\sqrt{\frac{EhD}{R^2}}$$

Equation (1) expresses the relationship between load and deformation in space and time. Let ξ denote the distance from the moving step so that $\xi = x - Vt$. Substituting this transformation into equation (1):

$$D\frac{d^4 w}{d\xi^4} + \frac{Eh}{R^2}w + mV^2\frac{d^2 w}{d\xi^2} = (1 - H(\xi)) \tag{2}$$

Equation (2), since it lacks the time variable, can be viewed as a *statics* problem in the *space* variable ξ. The solution to this 'statics' problem when V is subcritical is [1]:

$$W_s(\xi) = w/K = \frac{e^{d\xi}}{2}(-\cos c\xi + \frac{d^2 - c^2}{2cd}\sin c\xi) + 1, \quad \xi \le 0 \tag{3a}$$

$$W_s(\xi) = w/K = \frac{e^{-d\xi}}{2}(\cos c\xi + \frac{d^2 - c^2}{2cd}\sin c\xi), \quad \xi \geq 0 \tag{3b}$$

where $c = \gamma\sqrt{\frac{\lambda+1}{2}}$, $d = \gamma\sqrt{\frac{1-\lambda}{2}}$, $\lambda = V^2/V_{cr}^2$, and $\gamma^4 = Eh/R^2D$. $K = R^2/Eh$ approximates the Lamé displacement so that W_s represents the ***dynamic amplification*** caused by the moving step of pressure.

WALL DEFORMATION CAUSED BY AN ARBITRARY LOAD DISTRIBUTION

Consider a moving pressure, $f(\xi)$, where the leading edge is no longer a step but any function such that $f(0) = 0$ and $f(\xi) = 1, \xi \leq -\alpha$. Figure 2a is an example of such a pressure when $\alpha = 2.4$. The wall deformation W_f caused by this pressure distribution can be found using the expression for W_s above. To show this, we first envision a staircase approximation to $f(\xi)$, as shown in Figure 2b, so that $f(\xi)$ is approximated as a sum of step distributions each of magnitude Δf_i. η_i is the distance of the leading edge of the i^{th} step from the origin $\xi = 0$. The distance between the leading edges of two successive steps is then $\Delta\eta_i$. The displacement caused by the i^{th} step is simply:

$$W_i = \Delta f_i W_s(\xi + \eta_i)$$

Because of the linearity of Equation (2), N such displacements can be summed to give the displacement caused by an N-step approximation to $f(\xi)$, i.e.:

$$W_{N-step} = \sum_{i=1}^{N} \Delta f_i W_s(\xi + \eta_i) = \sum_{i=1}^{N} \frac{\Delta f_i}{\Delta\eta_i} W_s(\xi + \eta_i)\Delta\eta_i$$

Taking the limit of this sum as $N \to \infty$ and $|\Delta\eta_i| \to 0$, results in the integral:

$$W_f = \int_0^\alpha f'(\eta) W_s(\xi + \eta) d\eta \tag{4}$$

The simplest $f(\xi)$ is the linear function:

$$f(\xi) = -\frac{\xi}{\alpha}$$

Since η increases as ξ decreases:

$$f(\eta) = \frac{\eta}{\alpha}$$

so that

$$f'(\eta) = \frac{1}{\alpha}$$

Substituting for $f'(\eta)$ in Equation (4):

$$W_f = \int_0^\alpha \frac{1}{\alpha} W_s(\xi + \eta) d\eta \tag{5}$$

The integral in Equation (5) can be evaluated numerically once values for all parameters have been chosen.

NUMERICAL RESULTS

In this section, the response to a moving unit step, $W_s(\xi)$, as given by Equations (3a,b), is compared with that due to the 'ramp-step' $W_f(\xi)$ (Equation (5)).

The following parametric values correspond to a particular 60-mm gun tube:

$$E = 30.3 * 10^6\ psi \qquad \nu = 0.3 \qquad h = 0.12\ in \qquad \rho = 7.365 * 10^{-4} \frac{lb-sec^2}{in}$$

$$R = 1.2411\ in. \qquad V = 0.99V_{cr}$$

Using these values, $W_s(\xi)$ is computed using Equations (3a,b) and is shown as a dashed curve in Figure 3. From these equations the "wavelength" - that is, the distance between neighboring maxima - is $2\pi/c$ and computes to be 1.34 inches. For this example, this is the value also chosen for α, the length of the "ramp" portion of $f(\xi)$. The integral in Equation (5) can be evaluated numerically, and the resulting $W_f(\xi)$ is shown as the solid curve in Figure 3. The reduction afforded by the ramp is dramatic.

It is of interest to know the effect of ramp length, α, on the maximum response or dynamic amplification of the wall displacement. This is shown in Figure 4 - a plot of the maximum dynamic amplification resulting as α is iterated through increasing values in Equation (5). From the figure it can be concluded that the response is nearly minimized when $\alpha = 2\pi/c$, the value chosen for the numerical example above.

SECTION II - FINITE ELEMENT SIMULATIONS

The critical velocity theory employed in Section I assumes, among other things, a tube of infinite length. From actual field measurements, however, the most severe wall strains occur at or near the muzzle of a gun tube. These deformations are caused by reflections of the travelling wave at the muzzle which superpose with the remainder of the oncoming wave, at times reinforcing to create higher strain maxima. Predicting these strains via critical velocity theory, which assumes steady-state conditions,is not possible and the general procedure is to resort to numerical methods such as finite element simulations. While sucn simulations do not usually lead to a detailed understanding of the cause of the high strains (closed-form symbolic solutions like Equations 3a,b are not generated), they are useful to predict the strains on a case-by-case basis.

The finite element (ABAQUS) model used in this study is depicted in Figure 5. A constant ballistic pressure in the form of either a step or a ramp-step enters the breech end of a 60-mm gun tube at a constant velocity $V = 0.99V_{cr}$. The sudden appearance of this high velocity step of pressure at the breech end initiates a transient vibration that is not realistic of an actual firing. Previous work [5] shows that this transient continually interacts to give higher strain maxima at certain locations along the tube but decays with distance. While no evaluation of this effect has been undertaken for the ABAQUS results reported herein, based on previous experience it is not expected to be a major one. Its influence for the case of a ramp-step of moving pressure should be less than for a step.

Figures 6a-d compare the ABAQUS-computed time histories of the radial displacement at different points along the bore of the 60-mm tube in response to a moving step and a moving ramp-step of pressure. Figure 6a shows the response at a point midway along the tube, i.e., twenty-four inches from the muzzle and breech. Here the maximum displacement caused by the moving step is estimated to be 3.3 (times the Lamé displacement), whereas that due to the moving ramp-step is only 1.22. Since this location is considerably distant from the ends of the tube, both of these displacements should be, and are, in very good agreement with those predicted by critical velocity theory (Figure 3 of Section I). Figure 6b compares responses at a point only 0.24 inch from the muzzle end and shows a maximum displacement of 2.2 caused by the moving step vs. 1.40 caused by the moving ramp-step. Figure 6c compares time histories at a point which is 0.12 inch from the muzzle. The corresponding maximum displacements are 4.8 vs. 1.8. Finally, at the muzzle itself, Figure 6d shows the comparison to be 8.0 vs. 2.2. (In each figure the time of passage of the pressure front coincides with the abrupt increase in displacement. For example, in Figure 6a the pressure front passes this midlength location at approximately $t = 0.00052\ sec.$) While it is tempting to conclude that the ramp-step will *always* cause displacements (and hence stresses and strains), which are less than those caused by the step, finite element simulations such as these are never conclusive. A different choice of location along the tube; for example might conceivably yield opposite results. However, from the solutions obtained by the critical velocity theory in Section I, it is certain that at a *sufficient* distance from the ends of the tube, the

moving ramp-step always causes travelling waves of lesser amplitude than the moving step. It is reasonable to expect that the reflections of these waves will also be lower in amplitude.

CONCLUSIONS

From the work reported herein, it is apparent that dramatic reductions in dynamic strains in gun tubes can be obtained if the the ballistic pressure rise in the vicinity of the projectile can be made less abrupt. It is hoped that practical schemes for doing this are possible. One idea, suggested by Benet Laboratories Director Laurence Johnson [6], proposes an obturator band that has increasing wall thickness over its length. The inner surface of the obturator would receive the ballistic pressure and expand to contact the bore of the gun tube. The pressure applied to the bore by the obturator could then be brought to zero over the length of the obturator by suitably varying its wall thickness.

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5. T.E. Simkins, "The Influence of Transient Flexural Waves on Dynamic Strains in Gun Tubes," ARCCB-TR-89020, Benet Laboratories, Watervliet, NY, August 1989.

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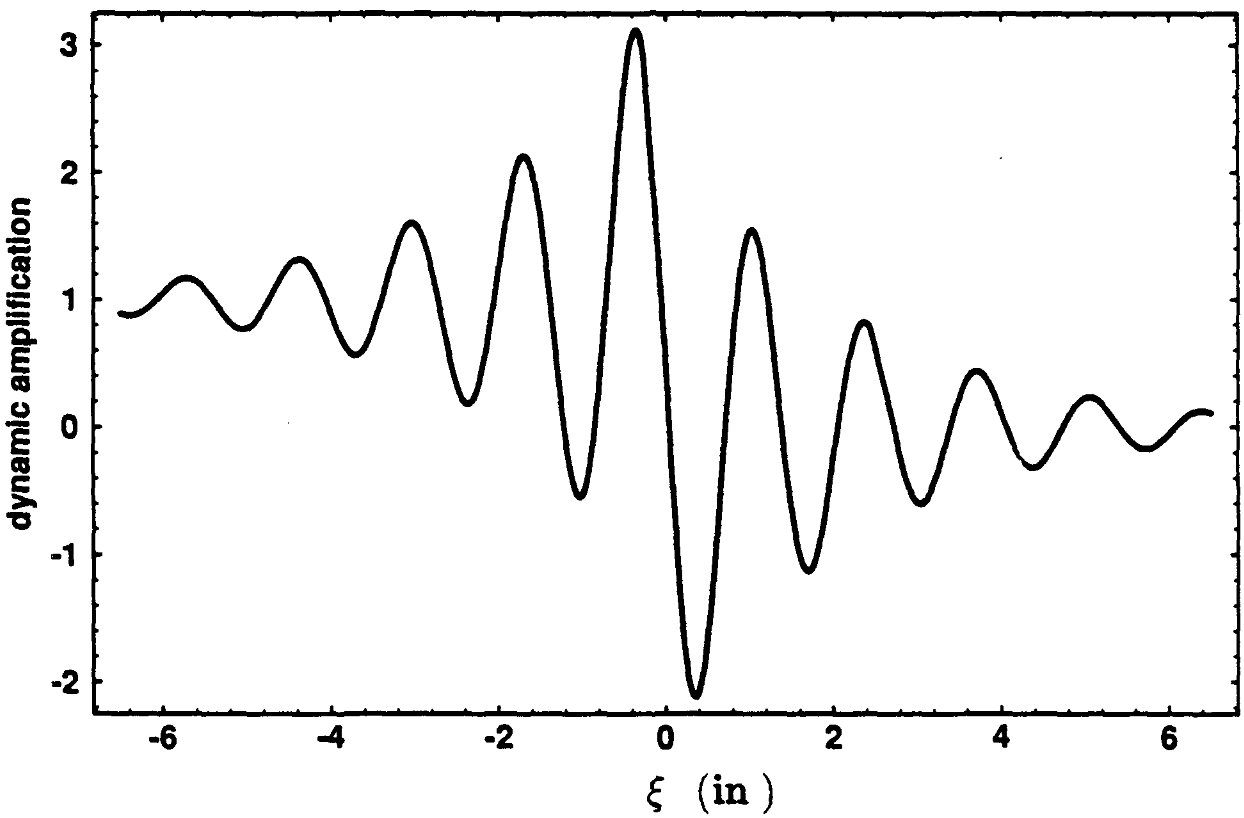


Figure 1. Dynamic amplification, $V = 0.99V_{cr}$.

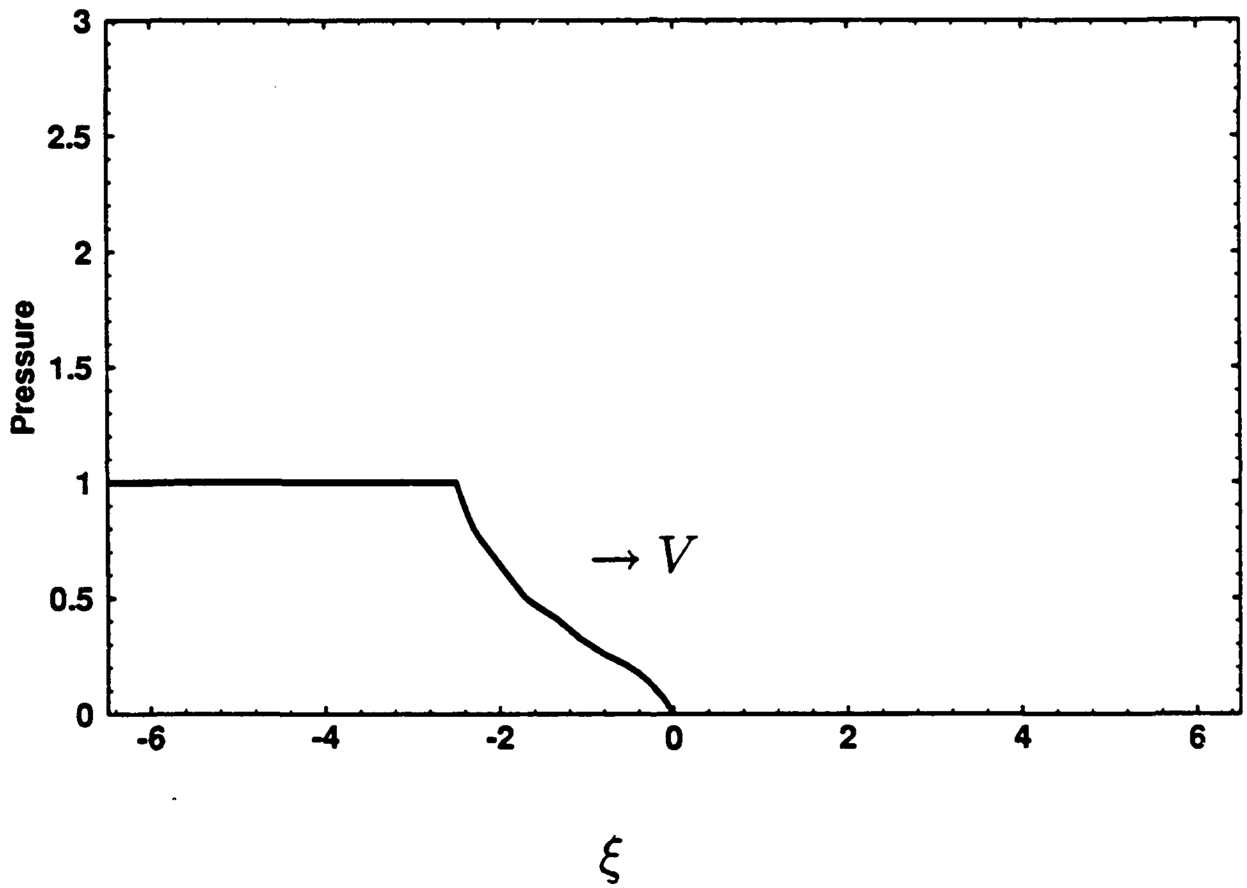


Figure 2a. Moving pressure, arbitrary leading edge.

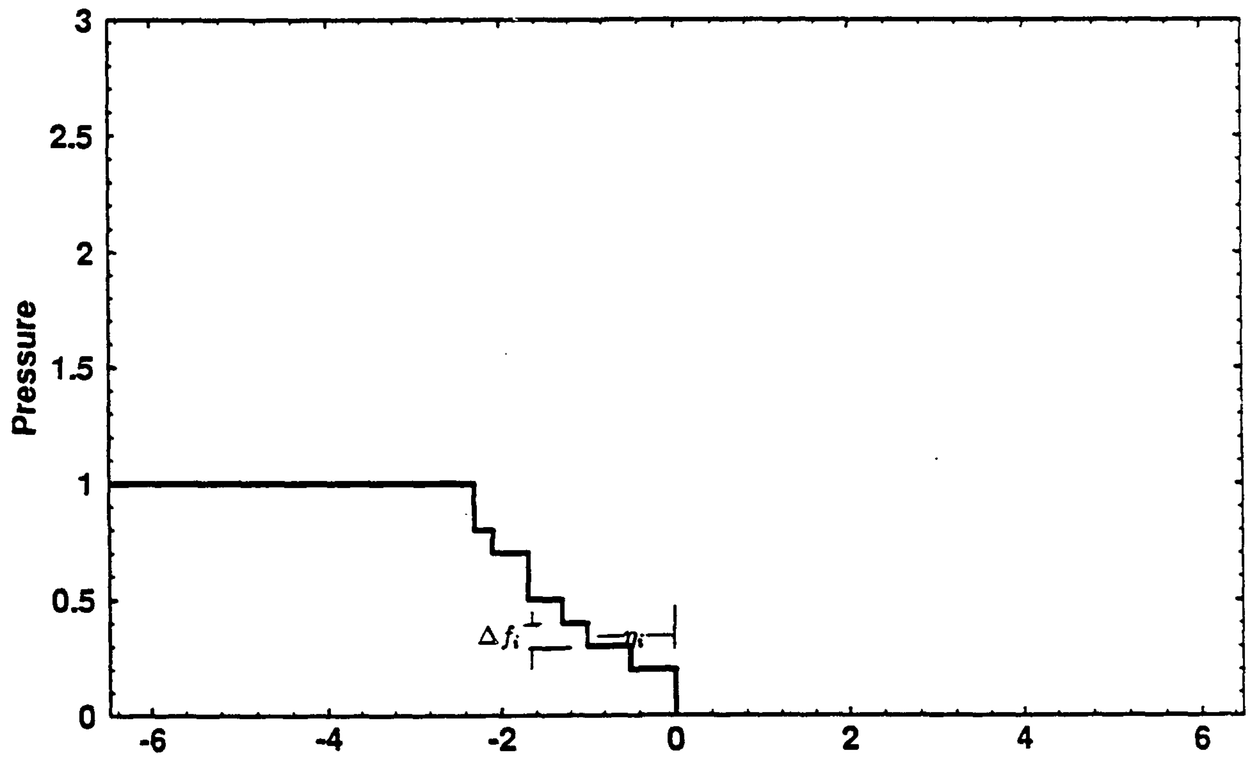


Figure 2b. Staircase approximation of Figure 2a.

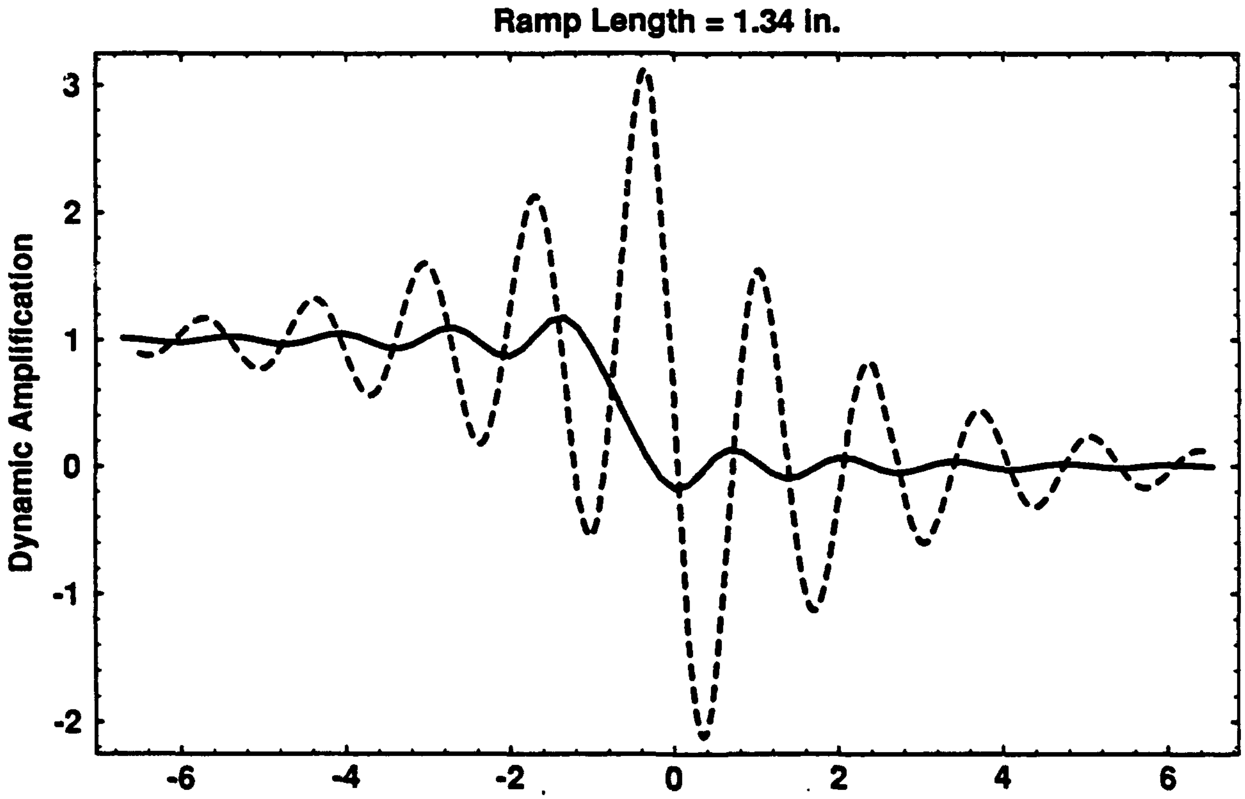


Figure 3. Comparison of response to step (dashed) and response to ramp (solid).

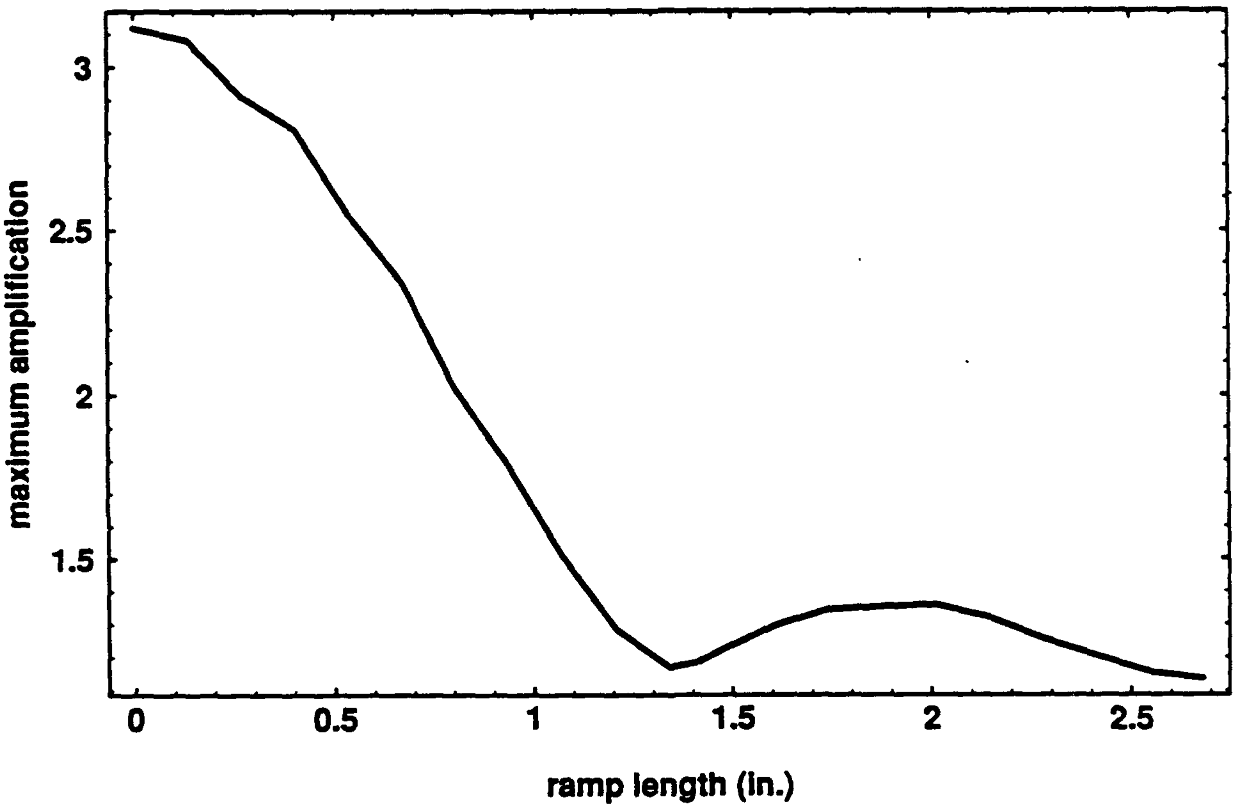


Figure 4. Effect of ramp length.

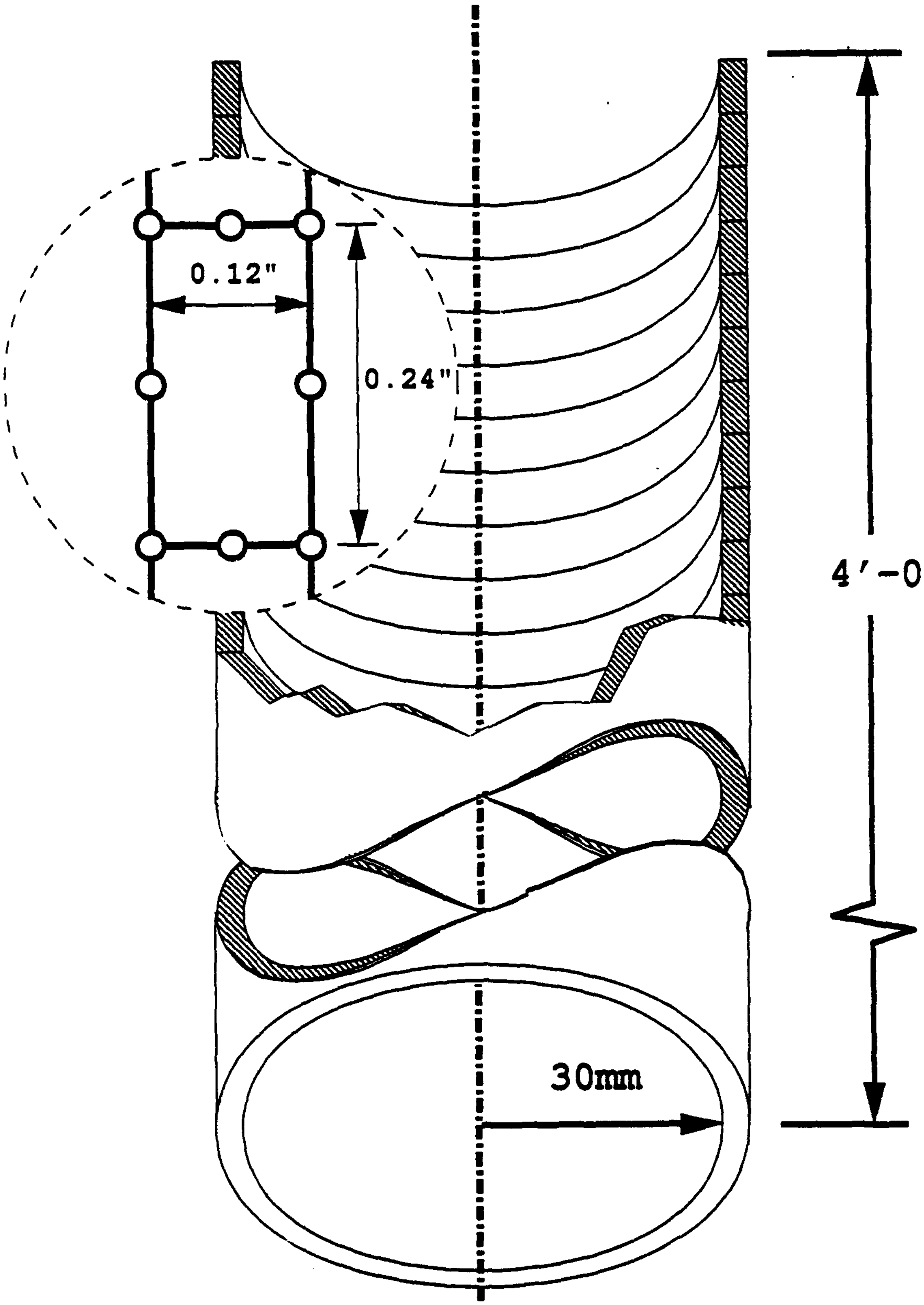
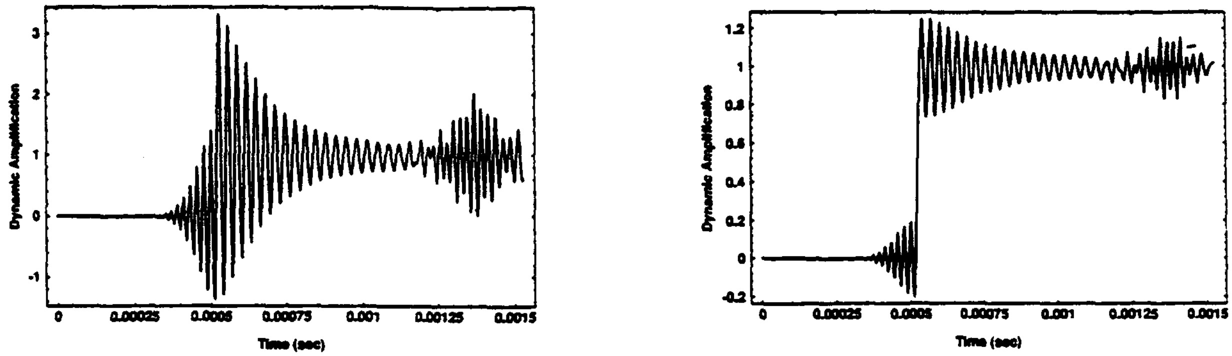
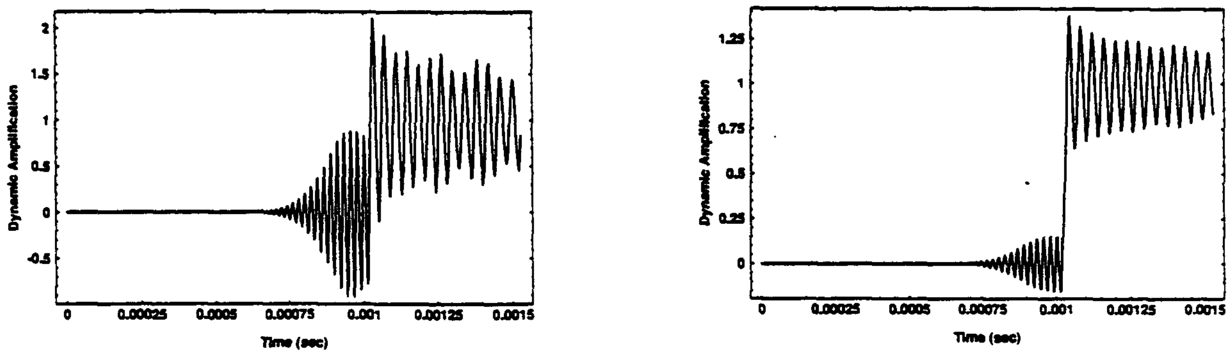


Figure 5. Finite element model.

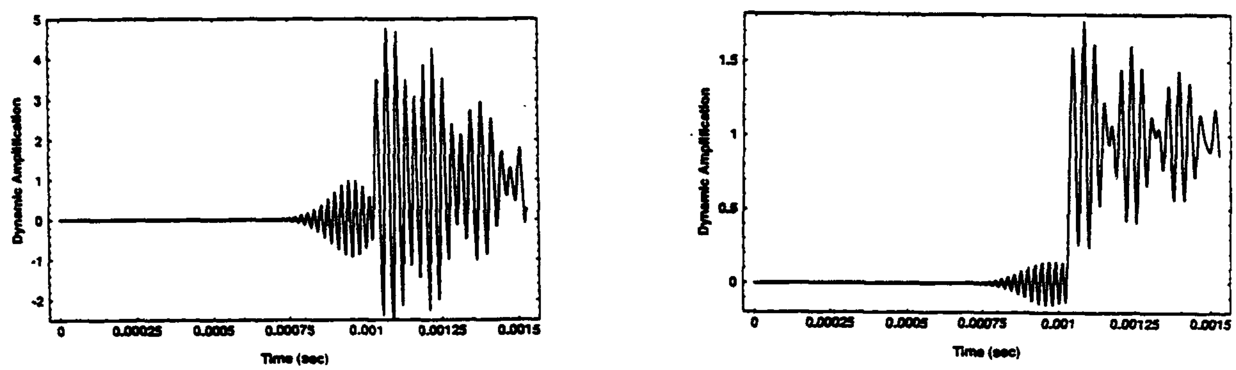
a) 24.0 in. from muzzle



b) 0.24 in. from muzzle



c) 0.12 in from muzzle



d) at muzzle

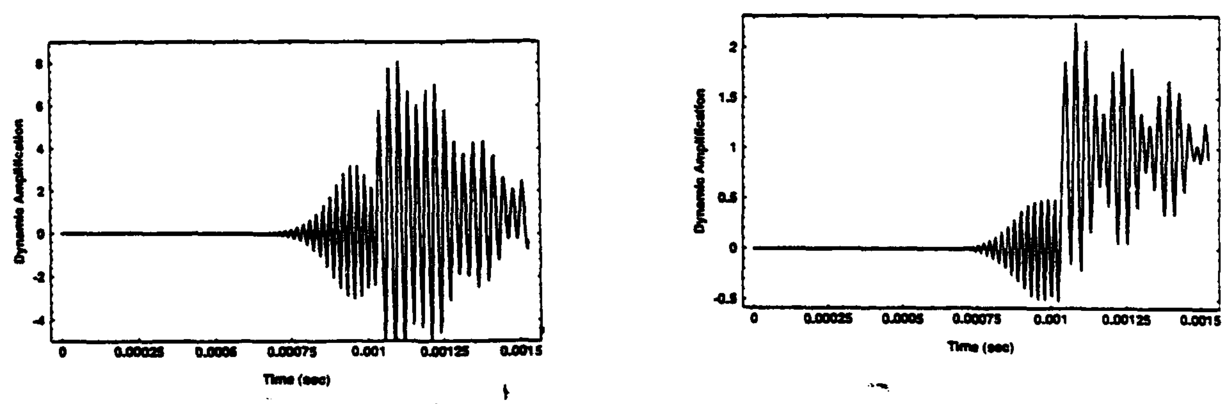


Figure 6. Response to moving step (left) and moving ramp (right).

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